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A Technique for Measuring the Gain of HF Antennas

J.K. Ayliffe, C.J. Coleman, G. Frazer,
K.W. Gooley, P. Hattam, J. Lane,
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Surveillance Systems Division
Electronics and Surveillance Research Laboratory

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ABSTRACT

A technique for characterising large HF antennas is considered. The approach achieves this by comparing radar returns from a target illuminated by the unknown antenna with returns from the same target illuminated by a well characterised antenna. Results from a trial confirm that the method is effective.

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Executive Summary

Antennas are a critical factor in determining the overall performance of an Over The Horizon Radar (OTHR) and their characterisation is an important aspect of Test and Evaluation (T&E) for the Jindalee Operational Radar Network (JORN). RFS (the antenna manufacturers) have used the NEC2 electromagnetics code to estimate the performance of the JORN antennas. Due to the limitations of NEC2 (limitations that still apply to the more recent NEC4) they simulate all antennas over a perfectly conducting plane and then add the effects of a finite ground screen by post processing the results. Experience has shown that this is a valid procedure when the ground screen is of the extent used in the JORN design. RFS have proposed to verify their predictions of antenna performance by means of port scattering tests. These would adequately verify the NEC modelling, but would not verify the post processing and hence the final gain patterns. It is these final gain patterns that are of prime importance and hence the Commonwealth would like to see verification of this aspect of the modelling.

To satisfy the Commonwealth requirement for the verification of antenna gain simulations, DSTO has developed a new measurement technique. The basic idea behind the approach is to estimate the radiation pattern of an antenna by comparing its measured radiation field with that of a well characterised reference antenna (usually a resonant monopole). The measurement is achieved by reflecting the radiation from both antennas towards a radar receiver by means of a large cross section target that orbits these antennas (the orbit being designed to allow comparison at all elevations and bearings of interest). Comparison of the returns at the radar receiver allows the determination of the relative gain of the antennas. Determination of the absolute gain then comes down to the much simpler task of characterising the reference antenna. The report describes the detail of the technique and the series of experiments that constituted its development and refinement.

The antenna measurement technique has now reached a stage in its development where Surveillance Systems Division (SSD) is confident in its ability to provide the Commonwealth with an effective characterisation of the JORN transmitter antennas. Consistent results have been obtained on numerous occasions and under a variety of conditions. The major remaining problem is to develop an automatic procedure for extracting data from radar recordings. An equivalent receiver antenna measurement technique is under development and results from initial trials look promising.

Authors

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Jim Ayliffe completed a Bachelor of Science degree in 1981 and a Bachelor of Engineering degree in 1982 at the University of Adelaide. In 1983 he joined DSTO and started work on the Jindalee Over The Horizon Radar project. The initial work involved the design, implementation and maintenance of the Jindalee signal processing and automatic tracking systems. Later work has mainly been concerned with system integration and testing issues for both the Jindalee and JORN radars.

C.J. Coleman
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Christopher Coleman is a mathematics graduate of Imperial College, London University and holds a PhD in Theoretical Physics from the same institution. Between 1974 and 1977 he held postdoctoral research positions at Imperial College and then at the University of Wales. From 1977 until 1984 he was a lecturer in the Theoretical Mechanics Department of Nottingham University. In 1984 he moved to Australia to take up a teaching position in the Mathematics Department of Wollongong University. He joined the High Frequency Radar Division of DSTO in 1989 and since then has been working in the areas of propagation modelling and antennas.

G. Frazer
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Gordon Frazer receive the B.E. (hons) degree from the University of Canterbury, in Christchurch, New Zealand in 1982; the M.Eng.Sc from the University of Queensland, in Brisbane Australia in 1990; and the Ph.D degree from the Queensland University of Technlogy in Brisbane, Australia in 1996. From 1982 to 1988, he worked in the Communications Section of the Queensland Electricity Commission, Brisbance, Australian, on various communications problems in the area of electricity transmission. From 1988 to 1990 he was with Mosaic Electronics, QLD, Ltd, Brisbane, Australia, designing real-time digital signal processing hardware and software. Since 1994, Dr Frazer has been with the Radar Processing and Tracking Group, Surveillance Systems Division, Defence Science and Technology Organisation, Salisbury, Australia, where he has been working on various signal analysis problems in high frequency (HF) radar. Dr Frazer's research interests are directed toward HF skywave and surface wave radar design.

K.W. Gooley

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Keith Gooley graduated from Adelaide University in 1970 with a Bachelor of Technology Degree in Electronic Engineering. He worked on ionospheric, glaciological and meteorological equipment for various Government Departments principally the Ionospheric Prediction Service until 1986 including 2 years service on Antarctic stations. After working in private industry for 18 months, developing HF communications equipment, he joined the then HF Radar Division of DSTO in March 1988 where he has worked on RF hardware aspects of HF radar development. Principal projects have been the extension of the FMS to 45 MHz, the 360° FMS and the RF Upgrade to the radar.

P. Hattam

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Peter Hattam has an Associate Diploma in Electronic Engineering from the University of Adelaide. He has worked at the Defence Science and Technology Organisation for 33 years. For 22 years he has been working on Jindalee HF Radar Systems and is currently a Technical Officer Grade 4 in Radio Frequency Design and Experiments Group, Surveillance Systems Division.

J. Lane

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John Lane started as an apprentice with DSTO in 1970. After completion, while studying for his Associate Diploma, he had several attachments to electronic laboratories until joining the HF Radar Division in 1977 as an Electronic Technician. He has been associated with the Jindalee Project since joining HFRD (SSD) in 1977 and has been involved in managing several electronic laboratories as well as 75 remote field trials Australia wide, researching skywave and groundwave propagation properties

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Adrian Pincombe graduated in mathematics from the University of New South Wales and worked for fourteen years in operations research before completing an M.Sc. and a Ph.D. in applied mathematics at the University of Wollongong. He took up a teaching position in the School of Mathematics at the University of South Australia in 1993, before joining DSTO in 1996. Since that time he has worked on the simulation of various aspects of radar.

E. Sweetman
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Elizabeth Sweetman completed a Bachelor of Applied Science in Computer Studies in 1991 and is currently undertaking a Bachelor of Engineering in Computer Systems Engineering at the University of South Australia. She spent three years in the private sector developing software to support business activities in the areas of finance, marketing, warehousing and distribution. Elizabeth commenced work with DSTO as an Information Technology Officer in 1994, developing computer applications to support research activities in the "Ionospheric Effects" group. She is currently employed as a Professional Officer within Surveillance Systems Division as part of a research team providing real-time surveillance information to the Royal Australian Air Force.

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1. Background

Antennas are a critical factor in determining the overall performance of an Over The Horizon Radar (OTHR) and their characterisation is an important aspect of OTHR Test and Evaluation (T&E). RFS have used the NEC2 electromagnetics code to estimate the performance of the JORN antennas. Due to the limitations of NEC2 (limitations that still apply to the more recent NEC4) they simulate all antennas over a perfectly conducting plane and then add the effects of a finite ground screen by post processing the results. This is a valid procedure since experience has shown that the antenna currents stabilise for ground screens that extend a quarter wavelength or more from the antenna structures (a condition that is easily met by the current JORN design). The port scattering tests proposed by RFS will adequately verify the antenna current distributions since port parameters (VSWR and S matrix) are highly sensitive to them. The currents are the raw material for the post processing that produces the antenna gain patterns over a finite ground screen. The postprocessing is based on the compensation theorem, but needs to use some approximation procedures in its practical implementation. Recent theoretical work in Surveillance Systems Division (SSD) indicates that these approximations are well justified. There has, however, been no attempt to compare this modelling with measured gain patterns. Such a step is important since the modelling makes several idealisations (electrical and topographic) concerning the screen and surrounding ground.

The performance of the radar is critically dependent upon adequate realised gains. Consequently, it is important that the modelling be validated for a suitable subset of conditions in order to build confidence in its predictions. If the measured gains show significant deviations from the modelling, a more comprehensive measurement program will be necessary in order to ascertain whether the antennas still allow the specified system performance to be achieved. Since the T&E in several areas of radar performance will rely on antenna modelling, it is crucial that the correct antenna gain patterns be available.

Given the above, SSD feel that T&E for the pattern aspect of antennas is an important issue and cannot be ignored. Whilst a complete experimental characterisation of these patterns is desirable, it is accepted that this is probably impractical. What is needed are sufficient tests to cover those parts of the pattern that are crucial to the achievement of the required system performance and to validate the modelling procedures that are used by RFS to derive the complete antenna patterns. From a propagation viewpoint, the most important elevations are those between 3 and 30 degrees. Modelling studies of propagation show this to be the range of elevations that are required to meet the specified radar coverage (taking into account diurnal and sunspot variations).

The practical issue of pattern measurement is the major hurdle in the validation of the modelling. Due to the size of the arrays, the far field will be of the order of 5 Km or more from the Tx array (as much as 2000 Km in the case of the Rx array) and so most measurements will involve some sort of airborne platform. SSD has made some investigations of the options and the following report describes some of its attempts to produce a suitable antenna measurement procedure. Starting from some initial ideas, there has been an evolution towards what SSD now believes to be a viable technique. The current report describes the series of experiments that have led SSD to this conclusion.

2. The Basic Technique

The basic idea behind the current approach is to estimate the radiation pattern of the antenna under test by comparing its measured radiation field with that of a well characterised reference antenna (usually a resonant monopole). The comparison is achieved by reflecting both sets of radiation from a large target that orbits these antennas (the orbit being designed to allow comparison at all elevations and bearings of interest) and comparing the returns at a suitable radar receiver. In order to distinguish the returns from the different antennas, the test antenna transmission would be sideband modulated so as to exhibit a significant 'Doppler' shift. SSD carried out some trials on this approach in June 1996 and used a PC Orion aircraft as the target. Although there was some limited success, there were several lessons that caused a rethink of the approach. The main problem experienced during the Orion trials (two were performed) was the large fluctuations in signal strength caused by a continually changing target aspect. (This was aggravated by a paucity of samples caused by the high speed of the target.) Fluctuations 'per se' are not a problem since the method only uses relative strengths. There were, however, several occasions on which the aircraft totally disappeared. To alleviate this, it was decided to consider an alternative target consisting of a helicopter with a resonant half-wave element suspended below the craft (the element being weighted in order to keep it near to the vertical). Although the cross section of a helicopter is small, a resonant antenna has an extremely large cross section (larger than that of the Orion). Such a target would be both cheaper and more reliable (the dipole cross section being fairly constant for the elevations of importance). Since a helicopter travels relatively slowly, however, Doppler discrimination between direct radar returns, and clutter, could be a problem. Consequently, it was decided to switch the element at its centre with a frequency sufficient to allow it to be Doppler discriminated on the radar. In this new approach, discrimination between antennas was achieved by adding a delay to the reference antennas so as to place its returns at a different range.

3. The Port Wakefield/Price Trials

The initial trial of the new antenna measurement technique was performed on the transmitter antenna of the SSD Surface Wave Radar (SWR) in South Australia (transmitter site at Price and receiver site at Port Wakefield). On the occasion of the first trial there were a large number of equipment problems and no conclusion could be reached about the test. There were, however, a number of important lessons learnt and these eventually led to the success of the venture. The equipment problems were sorted out and the methodology refined. Figure 1 shows the full target consisting of the Helicopter with dipole suspended underneath. The dipole modulation is provided by an electronic on/off switch that operates at a frequency of 5 Hz. The weight used in the experiment was 5 Kg and was sufficient to keep the dipole more or less vertical throughout the experiment. The intended plan was fly downrange of boresight with a steadily reducing height starting at 600m and finishing at 100m when 2 Km downrange (see figure 2a). The helicopter would then fly one and a half times around the array (see figure 2b), a full circuit at a height of 400m and a half circuit at a height of 800m. Finally, the helicopter would fly in from 2 Km to the rear of the array, starting at a height 100m and reaching a height of 600m when over the array (see figure 2c). The intention of flight segment 2a was to measure the boresight elevation pattern, 2b to measure the azimuthal patterns at approximate elevations of 11° and 22° and 2c to measure the

rear elevation pattern. Obviously it is only possible for the helicopter to attain the configurations approximately (figure 3 shows the flight that was actually achieved) and so a GPS logger was carried on the helicopter in order to provide data for the necessary adjustments. The tests were carried out at a radar frequency of 11.44 MHz using a waveform repetition frequency (WRF) of 62.5 Hz and a bandwidth of 8 kHz. Figure 4 shows a typical Doppler range display that was recorded during the experiment with the upper returns produced by illumination from the reference antenna and the lower returns by illumination from the antenna under test (the transmit antenna at Price).

Figure 5 shows a horizontal gain pattern (approximate elevation 16°) derived from the trial measurements (experimental points shown as diamonds) and figure 6 shows the boresight elevation pattern. In the SWR study, the antenna under test consisted of an array of eight broadband monopoles (spacing of 10.5m and endfire phasing). This has a theoretical beamwidth of about 60° which is consistent with the derived pattern. It will be noted that the elevation patterns have a very poor response at low elevations and this is consistent with the small ground screen (only 20m by 100m) of the system. In general, the results were in line with the expected response of the antennas, but with a large scatter. The scatter, however, was inevitable due to difficulty experienced with the correct positioning of the helicopter (a problem that is evident from figure 3). For the azimuth gain plot, the variations in helicopter altitude required the use of results from elevations that varied by as much as 1.5° either side of the notional elevation (16°). Likewise, the elevation plot required the use of results from a fairly wide range of azimuths. The positioning problems with the helicopter were mainly due to its small size and resultant difficulties with winds. Consequently, it was decided that a larger helicopter would be needed in the 1RSU trials of the technique. A further problem was the inaccuracy of GPS estimates of helicopter altitude (important for estimating the elevation angles) and it was decided to use a differential GPS approach in the trials on the main OTHR (1RSU) at Alice Springs.

4. The 1RSU Trials

The next stage in the development of the technique was to perform a test on the 1RSU main Tx antenna at Harts Range. This antenna consists of a linear array of 8 log periodic antennas (LPDA's) spaced at 12 metres for frequencies below 12 MHz and 16 LPDA's spaced at 8 metres for frequencies above 12MHz. The first of these trials was performed in April of 1997. Lessons learnt on the previous trials led to the use of a more powerful helicopter and full GPS logging systems at Tx and Rx sites and on the helicopter. Furthermore, great care was taken with the mounting of the GPS antenna on the helicopter (loss of GPS lock had greatly reduced the useable data on some previous trials). The same test configurations (figure 2) were used, but with parameter changes to reflect the much increased far field distance from the Tx antenna. During the elevation tests, the helicopter height whilst over the antenna was set at about 2km and the maximum distance from the array at about 6km. For the azimuthal test, the helicopter was flown at a height of about 1km and a distance 6km from the radar antenna (corresponding to an elevation of about 11 degrees). The first trials were conducted with only one element of the transmit array driven (a test of the in array LPDA pattern). A frequency of about 11.5MHz was chosen since this would allow a test of the low band array (an array that was manufactured by RFS and can be regarded as a prototype for the JORN low band array).

The reference antenna was chosen to be a resonant monopole and its simulated pattern was used to translate the relative gains of test and reference into the gain patterns of the antenna under test.

Two experiments were performed on two separate days. In the first experiment the in array pattern of a single element was tested and in the second all elements were driven in order to test the beamformed pattern of the antenna. Experiments on the first day produced extremely good results (described below), but the second day was marred by equipment failures. The most important of these failures was the damage experienced by the modulator switching diodes (most likely due to static). Since this time, changes have been made to the modulator to make the unit less susceptible to such effects. No useful results were gained from the second day and so this report will concentrate on the results from the first day.

During the first day, the helicopter flew the missions shown in figures 2a-2c (the most critical mission (2a) was carried out twice). When the results were analysed, however, it was found that the helicopter had made considerable deviations from the flight plan and much of missions 2c and 2b were unuseable. Fortunately, however, there were sufficient observations to form the gain patterns shown in figures 7 (the boresight elevation pattern) and 8 (the azimuthal pattern over 180 degrees). The azimuthal pattern shows the expected behaviour, but the elevation pattern has some interesting deviations. It will be noted that gain above an elevation of 30 degrees is still fairly strong and close to the values measured at the expected peak (about 15 degrees elevation). This is in conflict with simulations (figure 9). Initially, it was thought that a possible explanation for this result was error in the extraction of experimental data (this had to be extracted visually from radar displays). Consequently, since the boresight elevation measurements were repeated, these experiments were analysed separately (the original plots were derived from the combined data). The separate analyses still showed the same elevation patterns and so extraction errors were ruled out. Inappropriate model assumptions could be a possible explanation. Indeed, the measured elevation pattern has the hallmarks of a ground screen with considerable surface impedance, different from the model assumption of zero impedance. NEC4 has been used to model more accurately the ground screen (a mesh of overlapping insulated wires) but, in the case of a monopole antenna, the results were fairly close to those from the original model assumption (zero impedance). It is possible that the anomalies arise from the more complex interaction of a full LPDA with the ground screen and investigations into this possibility in train. Another possible explanation is that the modulator was saturating in the stronger radiation fields and, as a consequence, changes were made to its design in order to lower this possibility in future experiments.

A second series of trials was performed at 1RSU in September of 1997. The power handling capacity of the modulator was increased in order to avoid the possibility of overload. In addition, the quality of the radar returns was greatly improved by using the north east pointing arm of the 360 degree FMS for reception. For these trials, a half radar (four beamformed LPDA's) was used and fed with a total of 10kw of power at 11.5MHz. Figures 10 and 11 show vertical and horizontal patterns derived from these experiments. In the case of the vertical pattern, the variation shows the same anomalous behaviour as in the previous set of trials. The horizontal pattern (measured at an elevation of 17 degrees) clearly traces out the main, side and back lobes of the antenna and shows the expected beam pattern (the beam was steered on boresight). From the figures, it will be noted that there is a slight asymmetry in the side lobes

(about 3dB) that needs explanation. Study of the returns from the reference antenna (a resonant monopole fed at 11.5MHz with a power of 10kw) revealed an azimuthal variation that was in line with this asymmetry. Furthermore, the pattern of variation was strongly suggestive of some residual ground screen effects. Although the reference antenna was placed two wavelengths away from the screen, the antenna pattern can still be strongly affected in directions that passed over the screen. In addition, there is the possibility that the numerous LPDA's at the site could also affect the reference pattern. These problems can be overcome by placing the reference antenna well to the fore of the screen for forward looking pattern measurements and well to the rear of the screen for backward looking measurements. Figure 12 shows the gain pattern of a monopole placed about two wavelengths away from a screen with dimensions consistent with those in the experiment. Looking away from the screen the pattern is relatively unaffected, but towards the screen there is considerable modulation of the pattern. Correction of the measured vertical pattern by this factor brings it more in line with the modelled pattern. Better placement of the reference antenna would, however, make such corrections unnecessary.

A third series of trials was performed at 1RSU in April of 1998 in order to test out the equivalent receive antenna measurement technique (to be reported elsewhere). In this series, the reference monopole was placed at about 250m to the fore of the array in order to eliminate ground screen and shading effects. Before the start of the receive antenna tests, a limited number of transmit antenna tests were undertaken with the new monopole configuration. The results clearly showed that much of the asymmetry in the horizontal pattern was a result of the positioning of the test monopole. If anything, there was now a larger response from the westerly side lobe, an effect that could possibly be a result of asymmetry in the test situation (only a half radar was used). In all, the results indicate that there can be fluctuations of the order of a dB around the expected sidelobe levels (13.6dB below the main lobe). Because of this, and to allow for experimental error, it is suggested that a 2dB margin be allowed (at the level of sidelobes and above) if the present scheme be used to verify antenna performance. Although there are still some deviations from the modelled pattern, the agreement is fairly good. Initial processing of the results showed much stronger deviations, but recent measurements of the monopole and ground screen dimensions have shown the original models for these aspects to be inappropriate and their remodelling has produced much closer agreement. There is still some deviation at elevations around 30 degrees and this will continue to be investigated.

5. Conclusion

The current report has described some trials of the viability of a technique for measuring the gain pattern of a large HF radar antenna array. In essence, the technique consists of comparing radar returns from a target that is illuminated by both the transmit antenna under test and a reference antenna of known gain pattern. The reference antenna is chosen to be small enough for conventional measurement techniques to used in determining its pattern. Furthermore, its returns are distinguished in range by driving it with a signal that has been slightly range delayed. A large stable target is provided by supporting a resonant dipole beneath a helicopter and, in order to distinguish the dipole from unwanted returns (helicopter and clutter returns), the dipole is modulated. The modulation consists of electronic on/off switching at its centre and this results in a Doppler offset equivalent to the switching frequency. The desired pattern is derived by

observing the target at a suitable number of points in the far field of both antennas and adding the difference (dB scale) to the known reference antenna radiation pattern.

Trials have shown that the above approach can be effective in determining the gain characteristics of a large transmit array. It is possible to extend the technique to receiver antennas, but this will only be practical for subarrays of the JORN system due to the large far field distances. The April 1998 trials included some receiver antenna tests (to be described elsewhere) and initial results look extremely promising. Further refinement of the technique is desirable and this will include software for automatically extracting observations of radar and reference antennas (this must be performed by hand at present). In conclusion, SSD is now confident that it has an effective technique for characterising the JORN antennas.

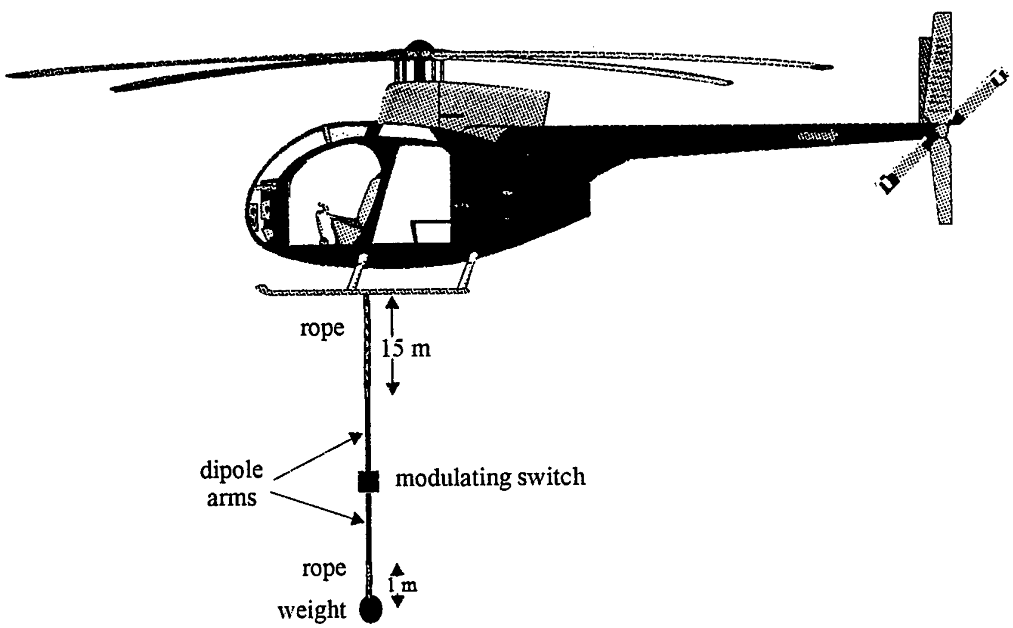

Figure 1: The Helicopter Target

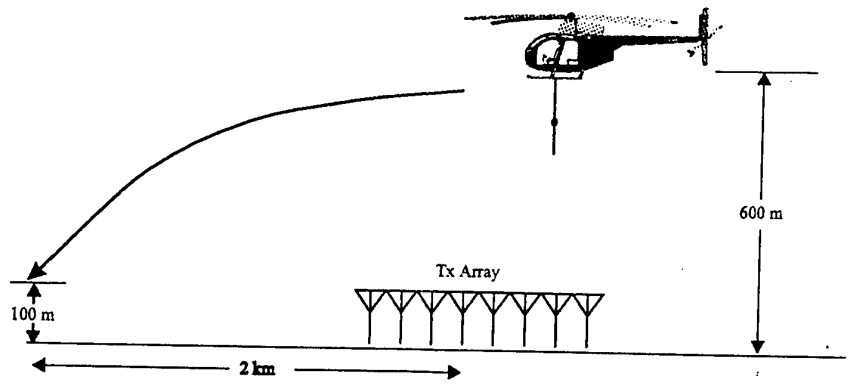

Figure 2a. Flight path to measure forward elevation pattern

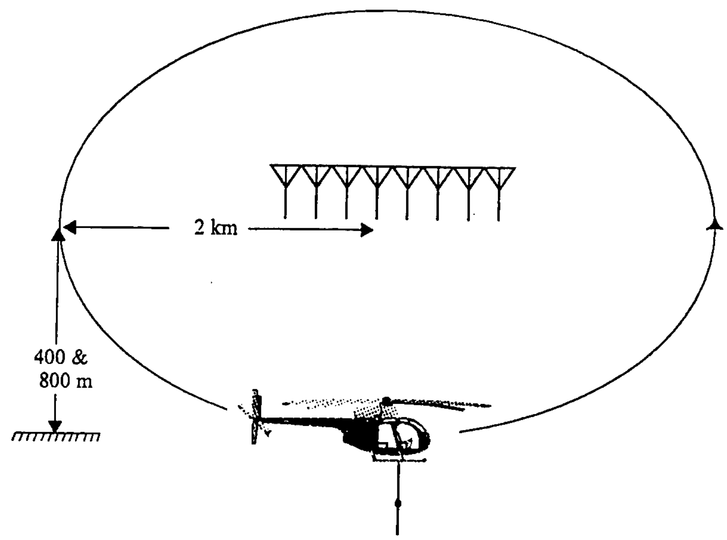

Figure 2b: Flight path to measure azimuthal patterns

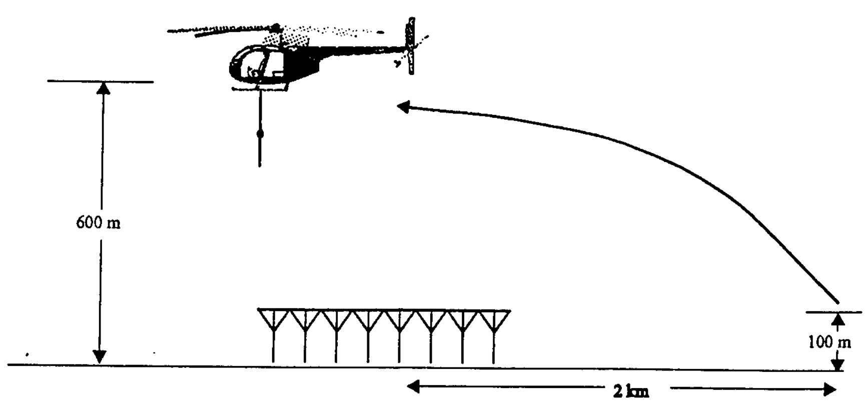

Figure 2c: Flight path to measure rear elevation pattern

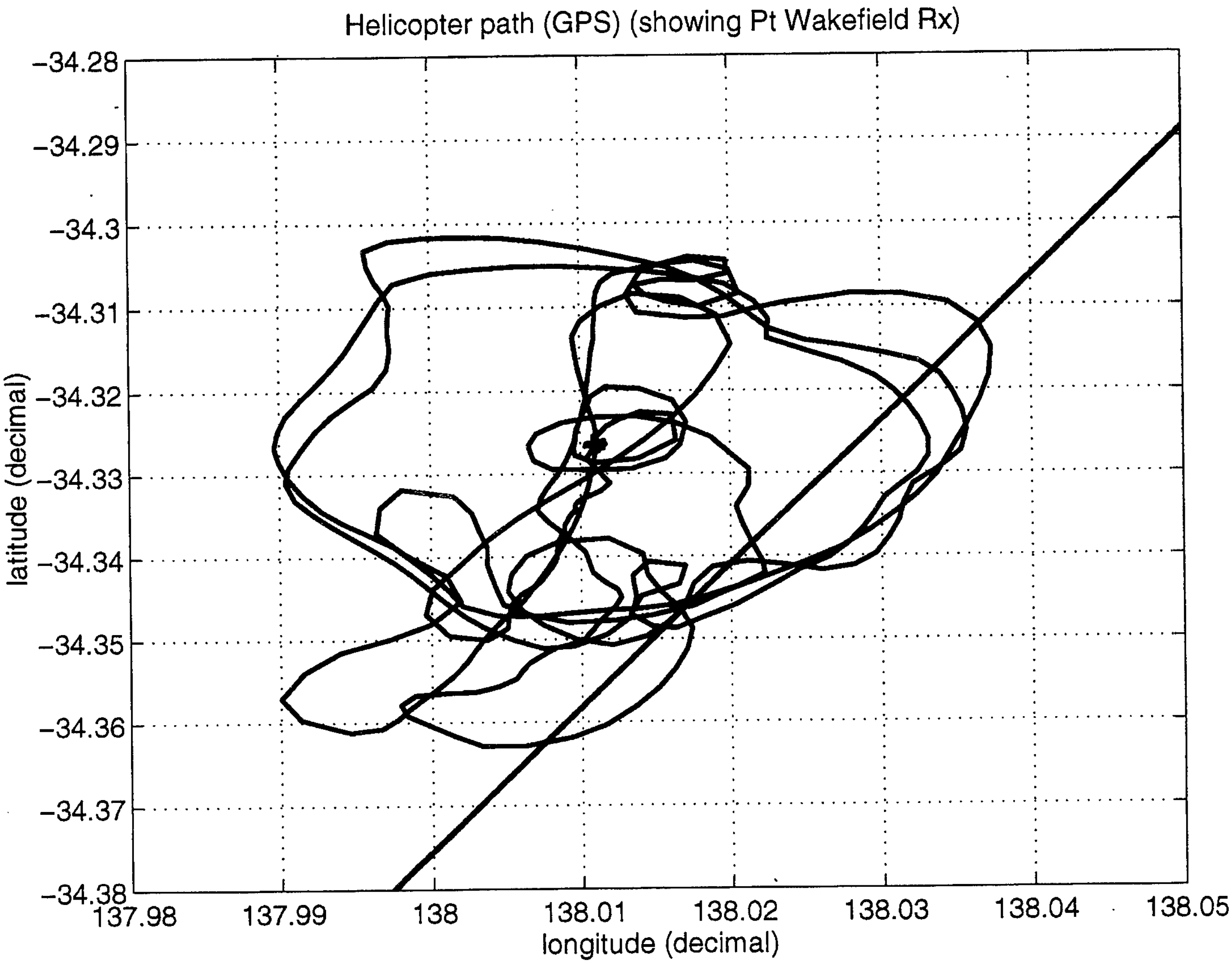

Figure 3: Helecopter Flight Path

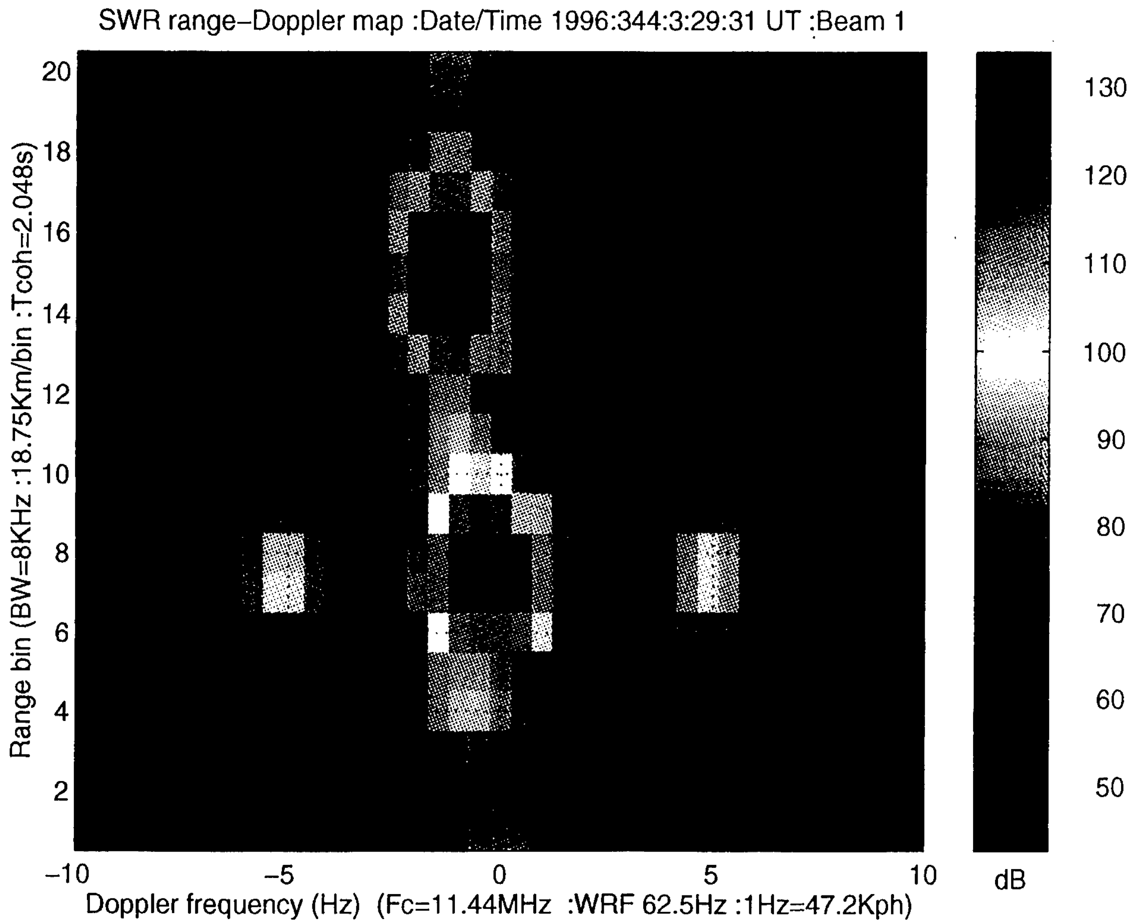

Figure 4: Range Doppler Map

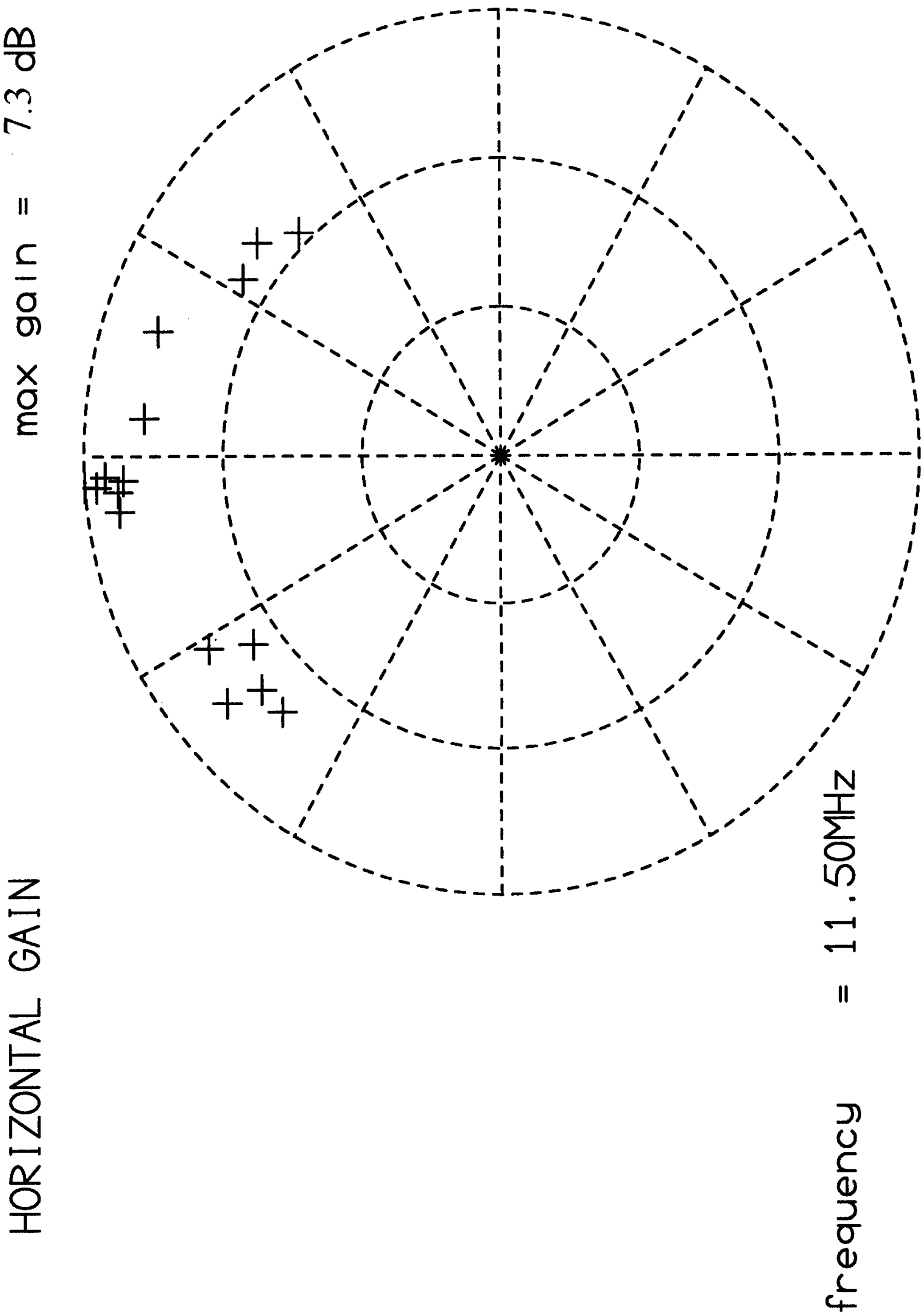

Figure 5: Measured Azimuthal Gains

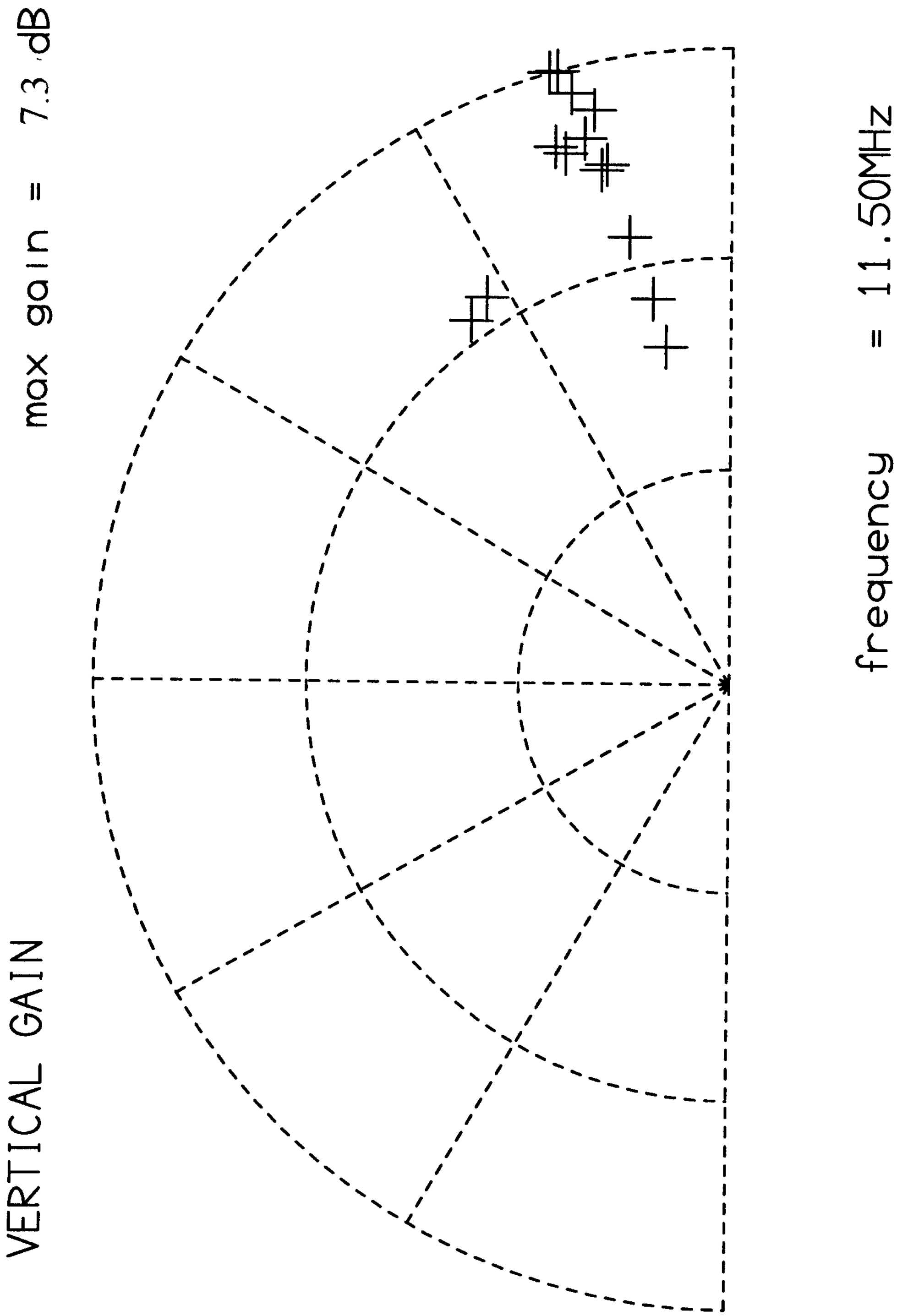

Figure 6: Measured Elevation Gains

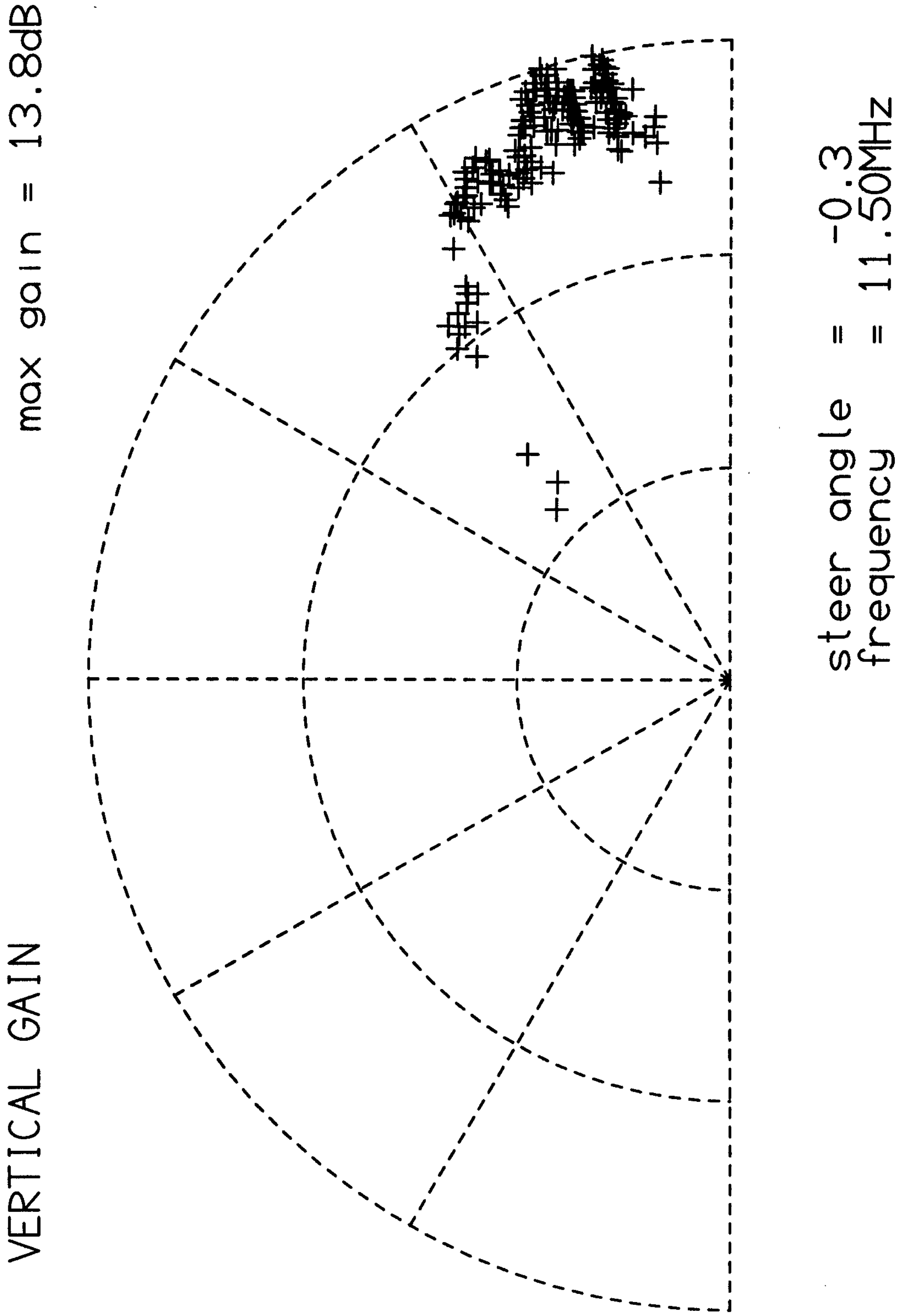

Figure 7: Vertical Gain Pattern (measured)

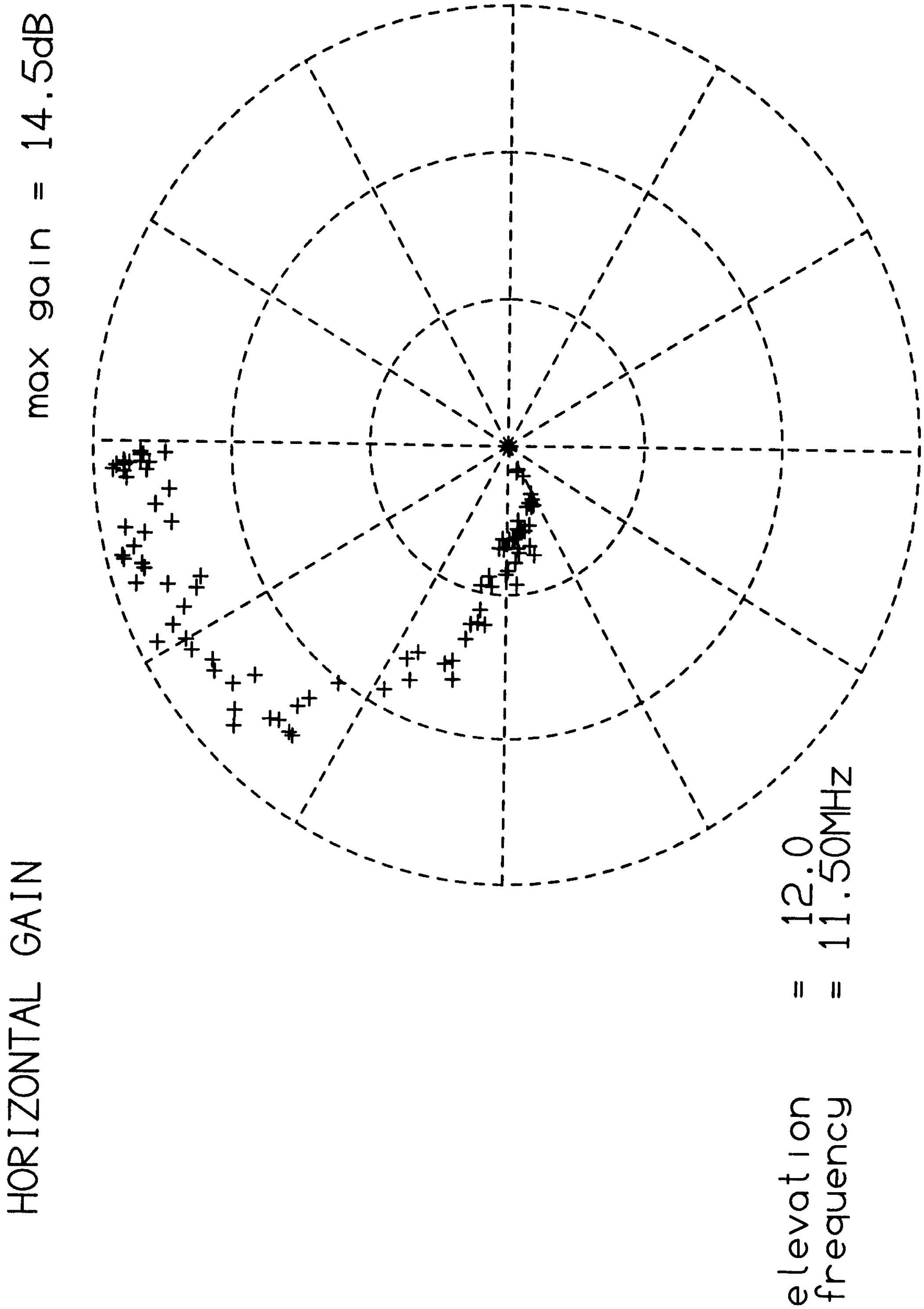

Figure 8: Horizontal Gain Pettern (measured)

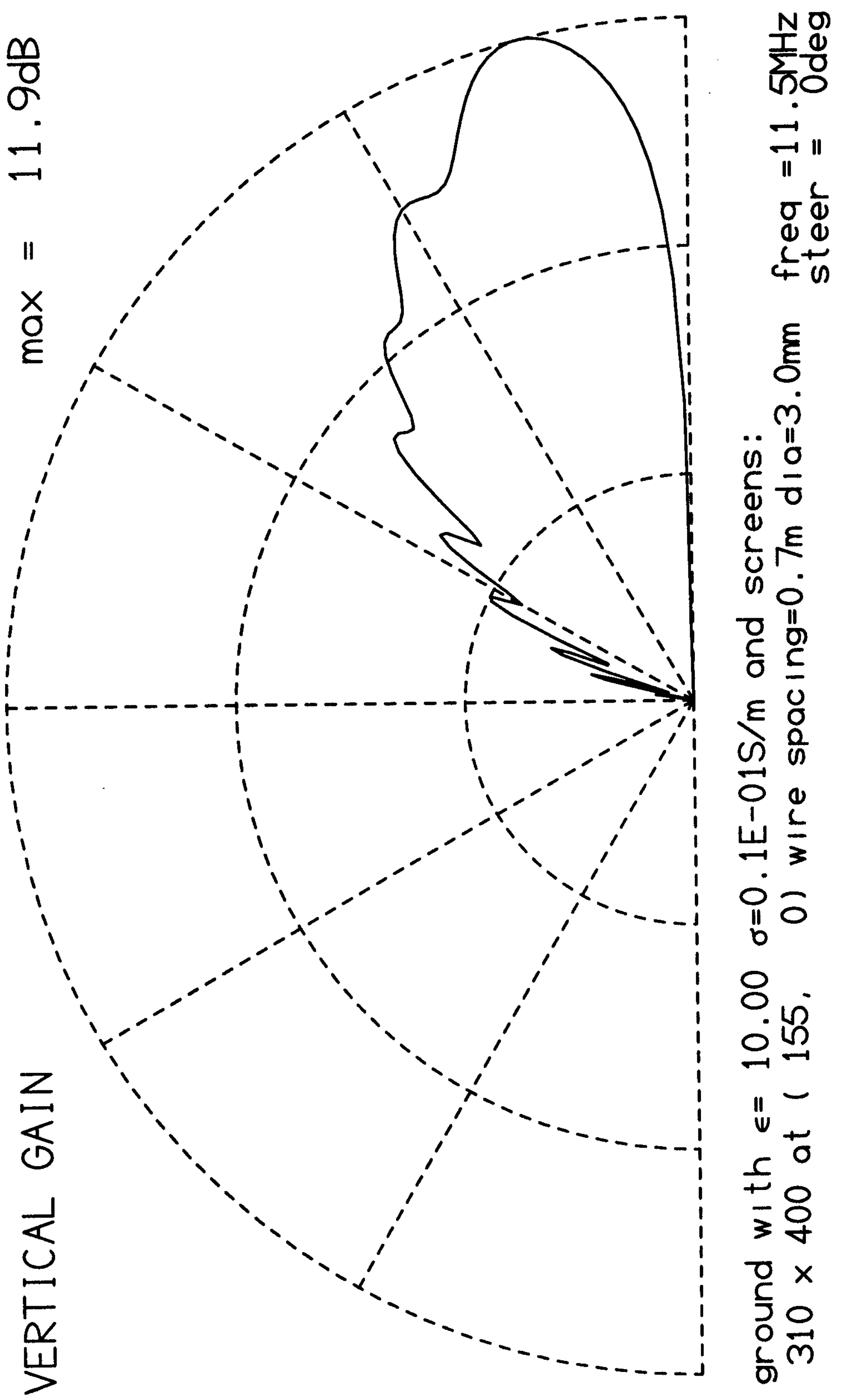

Figure 9: Vertical Gain Pettern (model)

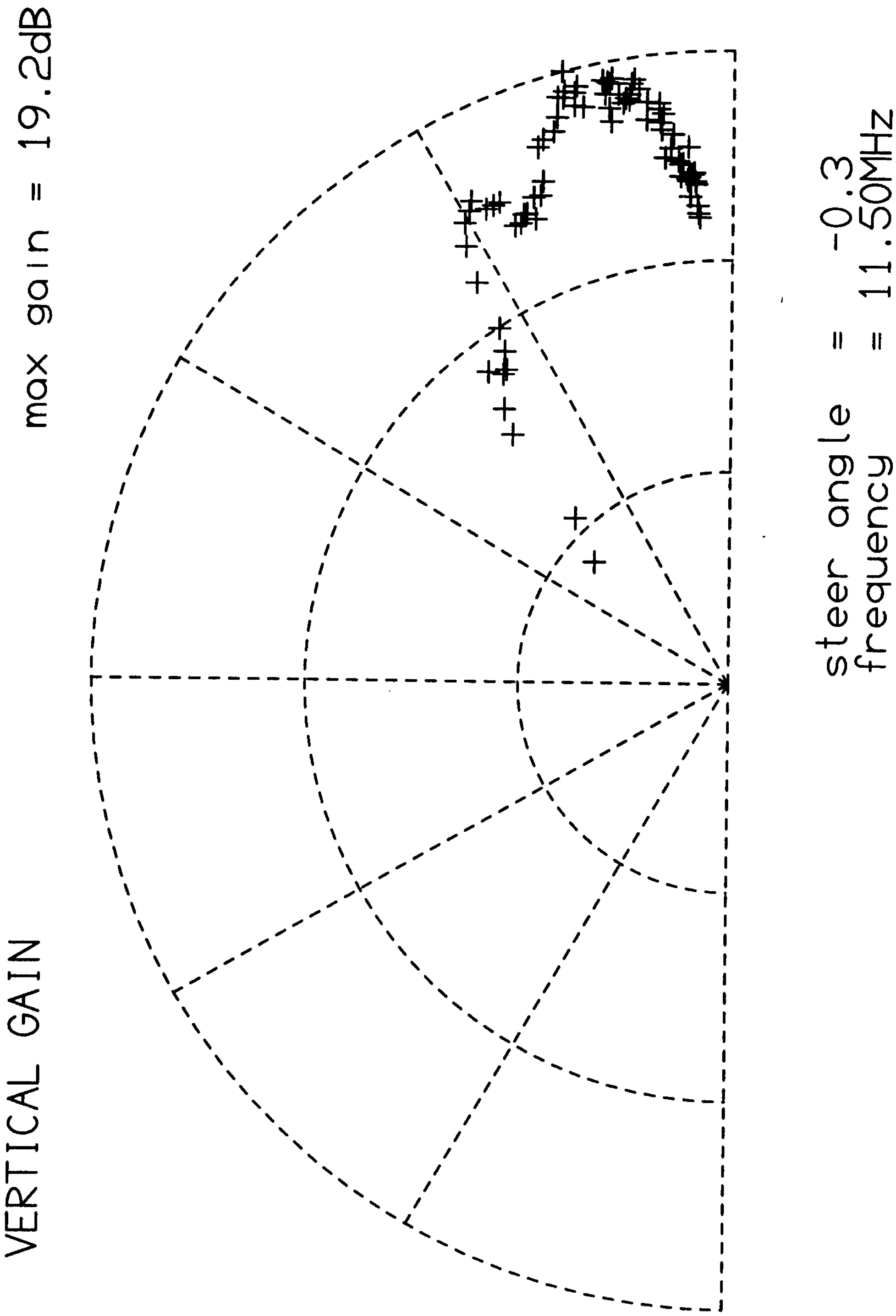

Figure 10: Vertical Gain Pattern (measured)

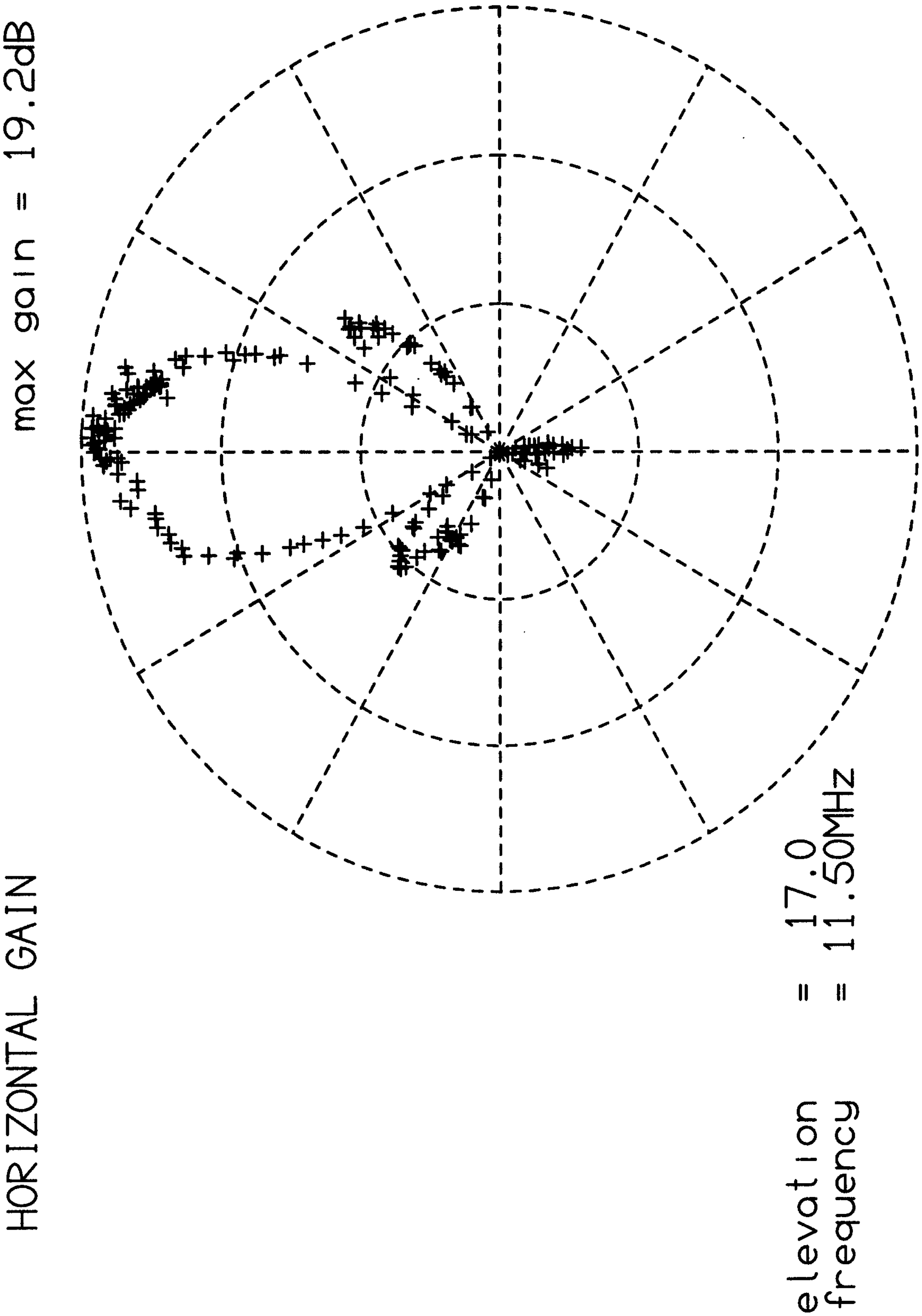

Figure 11: Horizontal Gain Pattern (measured)

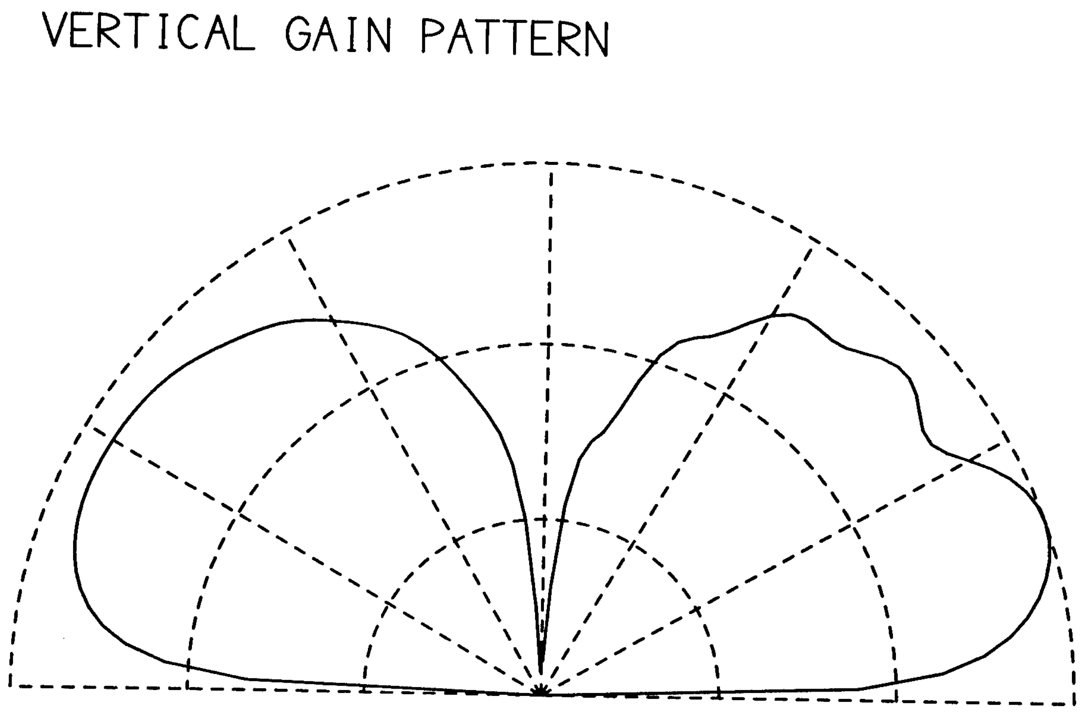

Figure 12: Effect of the Ground Screen on a Monopole (modelled)

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A technique for characterising large HF antennas is considered. The approach achieves this by comparing radar returns from a target illuminated by the unknown antenna with returns from the same target illuminated by a well characterised antenna. Results from a trial confirm that the method is effective.

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